Forecasting Electricity Demand and Planning for Renewable Energy Integration in a Semi-Urban Nigerian Community: A Case Study of Auchi, Edo State (2020–2033)

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***Abstract*: This study employed quantitative forecasting methods (Time Series, Regression Analysis, and Compound Annual Growth Rate - CAGR) to model future electricity consumption and population growth in Auchi, Edo State, Nigeria, spanning a 13-year horizon (2020-2033). Historical data (2020–2024), sourced from the Benin City Electricity Distribution Company (BEDC), revealed a significantly insufficient and unstable primary power supply, with an overall average daily availability of only 7.74 hours. Consumption analysis across three feeders (GRA, Auchi Town, and Igbe Road) showed consistent upward trends, with the socio-economically privileged GRA feeder demonstrating the highest demand. Population, projected to increase from 207,842 in 2020 to 281,352 by 2033, drives this demand. The analysis concludes that to meet the United Nation's energy per capita target (350 kWh/year for Auchi's semi-urban status) and address the growing deficit, the community will require a substantial increase in supplementary energy. Specifically, the required Photovoltaic (PV) supplementary energy is projected to peak at nearly 98 MW by 2033, confirming the critical need for a master plan focused on decentralized solar energy to ensure energy equity and security.**

***Keywords*: Load Forecasting, Population Growth, Renewable Energy, PV Supplementary Energy, Energy Per Capital.**

1. Introduction

Nigeria's power sector is constrained by low generation capacity, inadequate transmission and distribution infrastructure, and high aggregate technical, commercial, and collection (ATC&C) losses, resulting in unreliable electricity supply nationwide. These deficiencies disproportionately affect semi-urban and rural communities, limiting economic productivity and quality of life [1], [2]. Accurate electricity load forecasting is therefore essential for effective infrastructure planning, optimal resource allocation, and long-term energy sustainability [3].

Auchi, a rapidly growing semi-urban town in Edo North, typifies these challenges. Despite increasing population and commercial activities, electricity supply in the area remains unstable and insufficient, constraining socio-economic development and undermining progress toward global energy-access targets such as the United Nations' Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs) [4], [5]. Available grid-based power fails to meet basic residential and commercial demand, leading to chronic energy deficits.

This study addresses two key issues: (i) the projection of electricity demand in Auchi up to 2033 based on population growth trends, and (ii) the estimation of supplementary renewable energy capacity required to bridge the existing energy gap relative to international per-capita electricity consumption benchmarks [6], [7]. The outcome supports the development of a localized energy master plan aimed at transitioning from short-term supply mitigation to a sustainable and resilient electricity system.

2. Literature Review

A. Demand Forecasting in Nigeria

Electricity demand forecasting is a fundamental requirement for power system expansion planning, generation adequacy assessment, and policy formulation. In developing countries such as Nigeria, long-term electricity demand forecasting is particularly challenging due to rapid population growth, urbanization, and data limitations. Traditional forecasting approaches, including trend analysis, regression-based models, and econometric techniques, have been widely applied to estimate electricity demand using historical consumption, gross domestic product (GDP), and population indicators [8], [9].

Several studies have focused specifically on Nigeria's electricity demand. Iwayemi analyzed the structural determinants of electricity demand in Nigeria and emphasized the strong influence of population growth and economic activity on energy consumption [10]. Similarly, Adebola and Shahidehpour applied regression-based forecasting models to Nigeria's power sector and showed that inaccurate demand forecasts have contributed to persistent supply deficits and underinvestment in generation capacity [11]. These studies highlight the need for localized demand forecasting approaches that reflect regional demographic and socioeconomic characteristics, particularly for semi-urban areas such as Auchi.

Recent research has explored artificial intelligence and machine learning techniques to improve forecasting accuracy. Neural networks, support vector machines, and hybrid models have demonstrated superior performance compared to conventional methods, especially in capturing nonlinear demand patterns [12], [13]. However, their application in Nigeria remains limited due to poor data availability, inconsistent load records, and inadequate metering infrastructure, especially outside major urban centers.

B. Population Modeling and Energy Demand Linkages

Population growth is a key driver of long-term electricity demand, particularly in residential sectors. Common population forecasting techniques used in energy planning include arithmetic growth, geometric growth, exponential models, and cohort-component methods [14]. In many Nigerian studies, census-based extrapolation remains the dominant approach due to limited access to detailed demographic datasets.

The National Population Commission (NPC) census data have been widely used as a baseline for projecting population growth and associated electricity demand across Nigerian states and cities [15]. Oyedepo et al. demonstrated a strong correlation between population growth and residential electricity consumption in Nigeria, emphasizing that demand growth in semi-urban towns is often underestimated in national planning frameworks [16]. For towns such as Auchi, population-driven demand growth is further influenced by rural–urban migration, expansion of educational institutions, and increasing appliance ownership.

Studies combining population forecasting with per-capita energy consumption models have proven effective for estimating future electricity needs in data-scarce environments [17]. However, these models often rely on static assumptions regarding electrification rates and consumption patterns, which may not fully capture the evolving energy demand dynamics in rapidly growing semi-urban communities.

C. Photovoltaic (PV) Integration for Electricity Supply

Photovoltaic (PV) systems have emerged as a viable solution to Nigeria's chronic electricity shortages due to the country's high solar irradiance levels, averaging 5.5–7.0 kWh/m²/day across most regions [18]. Both grid-connected and off-grid PV systems have been widely studied as alternatives to conventional fossil-fuel-based generation, particularly for underserved rural and semi-urban areas.

Several techno-economic studies have demonstrated the feasibility of PV-based systems in Nigeria. Shaaban and Petinrin evaluated renewable energy potentials in Nigeria and identified solar PV as the most promising option for decentralized electricity supply [19]. Similarly, Olaniyan et al. developed a rural household load model and conducted optimal PV system sizing, showing significant reductions in cost of energy and capital expenditure when optimized configurations were employed [20].

Hybrid PV systems integrating battery energy storage, wind turbines, or diesel generators have also been shown to enhance reliability while reducing fuel consumption and emissions [21]. Babayomi et al. highlighted the growing role of mini-grids and decentralized PV systems in improving rural electrification across Sub-Saharan Africa, including Nigeria [22]. Despite these advantages, challenges such as high initial capital costs, intermittency, and limited policy support continue to constrain large-scale PV deployment.

D. Research Gap

Although extensive studies exist on electricity demand forecasting, population growth modeling, and PV system integration, most studies treat these components independently. There is limited research that integrates population forecasting, long-term electricity demand estimation, and PV system planning within a unified framework tailored to semi-urban Nigerian towns such as Auchi. Addressing this gap is essential for developing sustainable, data-driven energy planning strategies that support reliable electricity supply and long-term development goals.

3. Methodology and Research Design

A. Study Area and Research Design

This study employed a quantitative approach to develop projections for electricity demand. The methodology integrated both historical quantitative data and analytical projections to inform the plan's development.

The study area is Auchi, a community located in the Etsako West local government area of Edo State. Auchi was selected using purposive sampling primarily due to its regional importance and ease of data accessibility. The study population comprises all residential and commercial electricity consumers within this area, served by the Benin City Electricity Distribution Company (BEDC) via three primary 11kV feeders: GRA, Auchi Town, and Igbe Road.

B. Data collection

- Electricity Data: Monthly historical electricity supply figures spanning a five-year period (2020 to 2024) were obtained from the Benin City Electricity Distribution Company (BEDC) for the three distinct power feeders: GRA, Auchi Town, and Igbe Road. This data was used to analyze current consumption patterns and forecast future availability.
- Population Data: Historical census data from 1952, 1995, and 2006 were collected to establish a reliable long-term population growth rate for forecasting the size of the population to 2033.
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C. Methods of Data Analysis and Forecasting

The study utilized three principal forecasting techniques:

1) Population Forecasting: To estimate the growth rate of the study area, the compound annual growth rate (CAGR) formula as proposed by (Fernando, 2024) was adopted:

$$\mathrm{CAGR}\left(\frac{P_f}{P_t}\right)^{\frac{1}{t}} - 1 \qquad (1)$$

For this study, population forecast was based on the longest available time period, so the CAGR between 1952 and 2006, which is approximately 2.36% was used. Hence to estimate the population, the formula below was adopted

$$\text{Population Forecast} = P_0 \times (1 + \mathrm{CAGR})^t \qquad (2)$$

Where:

1. P_0 is the initial population in size
2. CAGR is the compound annual growth rate
3. t is the time period for the successive year

2) Electricity Consumption Forecasting: Two complementary methods were used to forecast electricity availability and consumption up to 2033:

Time Series Analysis (Least Square Method): This statistical technique was adopted to analyze the monthly electricity data, identify temporal structures, and develop a mathematical model for prediction. The Least Square Method was employed to fit a regression line to the time series data, minimizing the sum of the squared errors. The linear model is given by:

$$Y(t) = a + bt \qquad (3)$$

Where Y(t) is the dependent variable (electricity consumption) and t is the independent variable (time). The parameters a and b were estimated from the historical data.

Where:

$$b = \frac{n\sum xy - (\sum x)(\sum y)}{n\sum x^2 - (\sum x)^2} \qquad (4)$$

$$a = \frac{\sum y - b\sum x}{n} \qquad (5)$$

Here n = 12 (months).

3) Energy Consumption Per Capital and Supplementary Energy Calculation: Energy Consumption Per Capital: This is the ratio of total electricity consumed (or available) to the population estimate for each corresponding year. Auchi is classified as a semi-urban area, and the target per capita consumption, derived from the UN MDG 2015 energy access goals for the target year 2030 (urban 500 kWh/year, rural 250 kWh/year), was set at 350 kWh/year.

$$\text{Energy consumption} = \frac{\text{Electrical Energy Available}}{\text{Population of Auchi}}$$

Supplementary PV Energy Required: The difference between the targeted energy consumption (population\times 350 kWh/year) and the projected energy availability determines the energy deficit. This deficit is converted to the required PV supplementary power capacity (MW) necessary to bridge the gap and meet the UN MDG-related energy targets for 2030 and projected to 2033.

4. Results and Analysis

A. Historical Load Assessment (2020-2024)

The monthly historical electricity supply data from 2020 to 2024 are displayed table 1 to table 5

Table 1 shown the electricity consumption for the year 2020

The plot of energy consumption (KWh) versus monthly time for the year 2020 from Table 1 is depicted in figure 1.

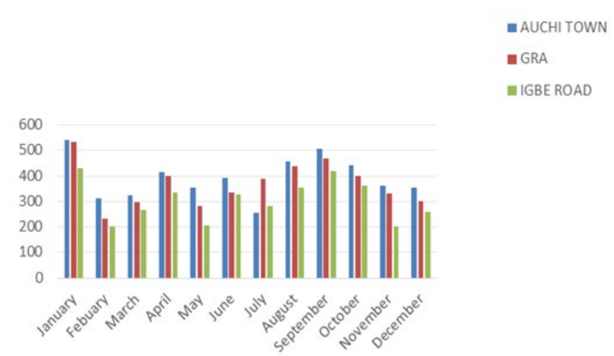

Fig.1. Electricity Consumption for 2020

Table 2 presents the monthly power consumption in the study area for the year 2021.Table

The plot of energy consumption (KWh) versus monthly time for the year 2021 is depicted in figure 2.

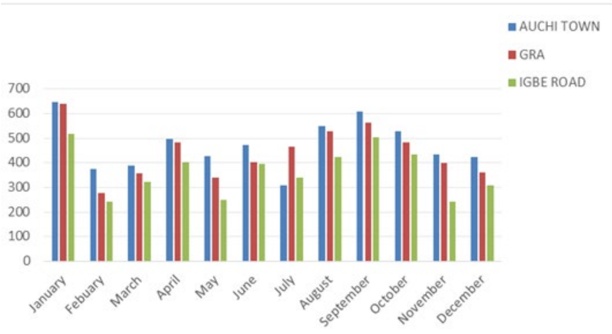

Fig.2. Electricity Consumption in Auchi for the year 2021

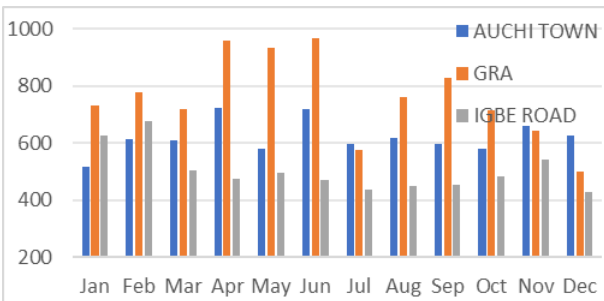

Fig. 3. Electricity Consumption in Auchi for the year 2022

Table 4 presents the monthly power consumption in the study area for the year 2023.

The plot of energy consumption (KWh) versus monthly time for the year 2023 is depicted in figure 4

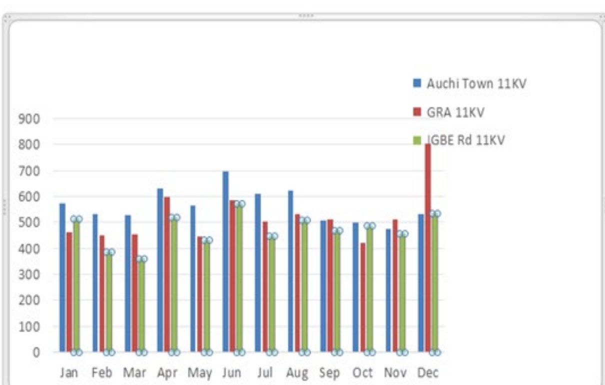

Fig.4. Electricity Consumption in Auchi Town for 2023

The plot of energy consumption versus monthly time for the year 2024 is depicted in figure 5.

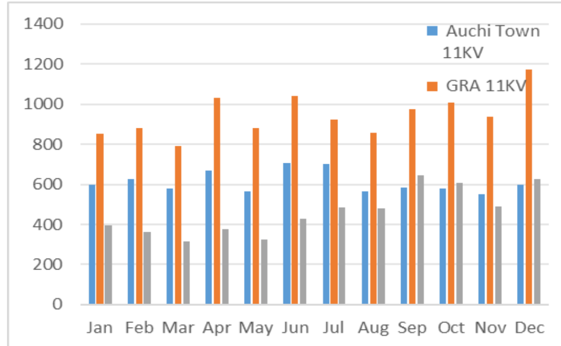

Fig. 5. Electricity Consumption for 2024

These three bar charts all display the Monthly Energy Consumption (in kWh) for three different areas served by an 11kV feeder: Auchi Town, GRA, and Igbe Road.

A. Annual Power Supply to Auchi From Benin Electricity distribution Company: The average annual power supply per feeder is presented in Table 6

$$\text{Total annual power supply} = \frac{\text{Total power supply}}{\text{Number of years}} = \frac{93667.97}{5}$$

=18733.59

$$\text{Average daily power supply (KW)} = \frac{\text{Annual power supply}}{\text{Months x Days x Time}} = \frac{18733.59}{12\text{x}30\text{x}7.74} = 7.461\text{KW}$$

The analysis of monthly consumption (Tables 1 to 5, Figures 1 to 5) highlights two critical findings:

1) Feeder Disparity: The GRA feeder consistently dominates consumption in most months and years (e.g., in 2024, GRA consumed 11348.7 KWh), reflecting a concentration of wealth, large power-intensive appliances (like air conditioners), and possibly more commercial activity. The Igbe Road feeder generally has the lowest consumption, suggesting socioeconomic differences or lower access/reliability. The observation concludes that the available energy is primarily channeled towards GRA and Town feeders for revenue generation as depicted in Table 4 to 5.

2) Severe Supply Shortage: The measurement of the daily average hourly availability of power (Table 4) confirms the insufficient supply. The overall daily average power supply to Auchi across the three feeders is calculated to be only 7.74 hours. This low figure underscores the grid's inability to provide a stable, 24-hour service.

B. Population and Load Forecast (2025-2033)

1) Population Growth: The population forecast based on the 2.36% CAGR is shown in Table 6 and Figure 6. The population is projected to grow consistently, rising from 207,842 in 2020 to 281,352 by 2033, representing a substantial 35.4% jump over the 13-year period.

2) Electricity Consumption Projections: The time series analysis using the least square method provided mathematical models and projection trends for each feeder. The trend analysis plots (Figures 7 to 8) indicate a clear upward trajectory for electricity consumption across all three feeders up to 2033.

GRA Feeder: The trend line captured a steady increase, with a mathematical value of Yt = 198.0 + 6.253t. This indicates a rising demand, likely driven by continued urbanization and affluence.

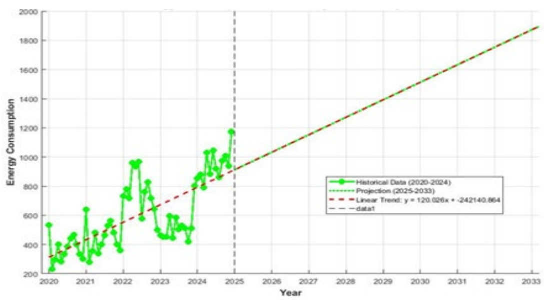

Fig. 6. GRA Electricity consumption Projection

Auchi Town Feeder: The projection showed the steepest monthly growth, with Yt = 214.9 + 6.554t, indicating a consistent growth in consumption.

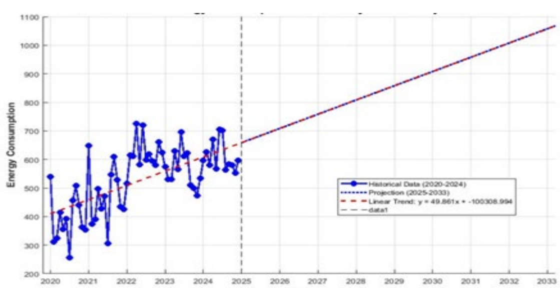

Fig.7. The trend results for Auchi town Electricity Consumption

Igbe Road Feeder: While starting from a lower baseline, consumption also showed an upward trend with Yt = 164.7 + 5.155t, indicating a need for infrastructure upgrade in this area to accommodate future demand.

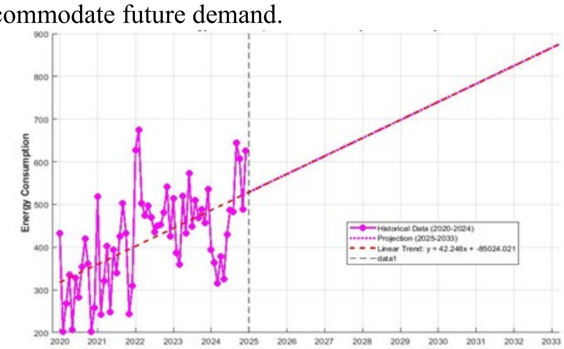

Fig.8. Igbei Electricity Consumption Projection

C. *Energy Per Capita Analysis and Deficit Assessment*

Table 1 presents an analysis of population and energy growth, detailing population growth trends, energy supply, and per capita energy availability.

Table.1. Analysis of population and energy growth

Year	Population	Energy availability (MWh)	Energy per capita (MWh)	Energy per capita KWh)	PV supplementary Energy needed (MW)
2020	207842	12777.425	0.061476626	61.147666	83.382
2021	212740	15332.941	0.072073615	72.073615	82.119
2022	217754	22596.37	0.103770171	103.770171	74.468
2023	222886	18714.743	0.083965538	83.965538	82.354
2024	228139	24213.83	0.095316921	95.316921	80.699
2027	244652	24531.531	0.100271123	100.271123	84.856
2030	262361	26617.418	0.101453409	101.453409	90.567
2033	281352	26728.321	0.099499957	99.499957	97.887

Figure. 9. illustrates the projected relationship between energy per capita and year.

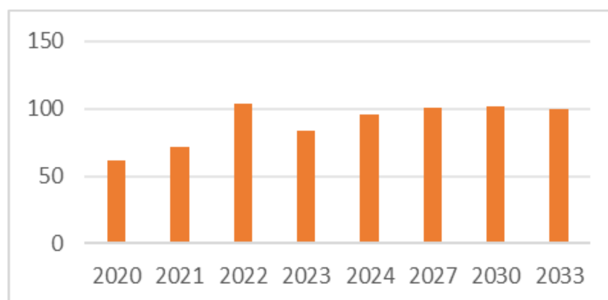

Fig.9. Energy Per Capita (KWh)

The energy per capita metric is a crucial indicator of energy equity. While total energy availability is projected to rise, the energy per capita value starts at a low of 61.1 KWh/person in 2020 and, despite some fluctuations, only reaches its peak of 103.7 KWh in 2022. The projections for 2030 and 2033 stabilize around 99.4 - 101.4 KWh/person. This stabilization is far below the adopted UN-related target of 350 KWh/person/year for Auchi as a semi-urban area.

The large and persistent gap confirms an energy deficit that the primary grid is fundamentally unable to address. The data from 2022 (peak per capita, lowest supplementary need) and 2023 (sharp drop in per capita, jump in supplementary need) highlights the volatility and unreliability of the existing primary energy supply system.

D. *Supplementary PV Energy Requirement*

The gap between the target consumption level (based on 350 kWh/year per capita) and the projected energy availability defines the required supplementary power capacity, as illustrated in Figure 10.

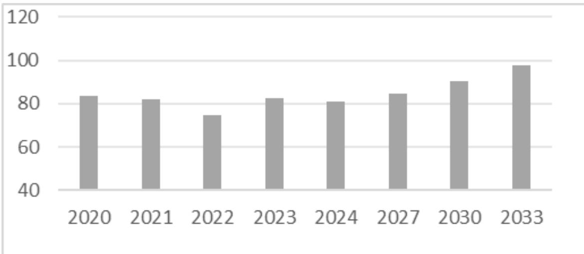

Fig.10. PV Supplementary Energy Needed

The PV supplementary energy needed shows a distinct and alarming upward trend in the later projection years:

2030: 90.567 MW required.

2033: 97.887 MW required.

This signifies that despite any planned increases in total energy availability (which are projected to rise), the demand of the growing population, especially when aiming for international standards, is growing faster than the supply. The projected need for nearly 98 MW of PV capacity by 2033 confirms that large-scale solar power is no longer an option but a critical necessity for Auchi to achieve energy security and improve its citizens' quality of life.

5. Discussion

The results of this study have significant implications for energy planning in Auchi and similar semi-urban communities in Nigeria.

The finding that the average daily power availability is only 7.74 hours provides empirical evidence of the crisis. This low availability necessitates high use of expensive, polluting fossil fuel generators by residents and businesses, which impacts public health and economic competitiveness.

The consistent, strong upward trend in consumption across all feeders, particularly the GRA and Auchi Town feeders, confirms that load growth is robust and will compound the existing supply crisis unless drastic measures are taken. The successful application of the Least Square Method and Regression Analysis provides reliable models for future planning.

Crucially, the energy per capita analysis reveals the true scale of the deficit. Even with increasing total supply, the projected energy consumption per capita of approximately 100 KWh is less than one-third of the target of 350 KWh/year. This massive shortfall points directly to the need for a non-grid solution.

The calculated supplementary requirement of 97.887 MW of PV capacity by 2033 provides a concrete, data-driven target for policymakers and energy investors. This capacity suggests a need for a large-scale, decentralized solar master plan that can feed power directly into the community, bypassing the limitations and unreliability of the central grid. Furthermore, targeting the higher demand feeders (GRA) and the least-served areas (Igbe Road) with dedicated microgrids could improve energy equity and system stability.

6. Conclusion

This research successfully utilized quantitative methods to forecast the load demand and quantify the energy deficit in Auchi, Edo State, Nigeria, for the period 2020–2033.

The key conclusions are:

- Supply is Grossly Insufficient: The current daily average power availability of 7.74 hours confirms a severe crisis in the primary energy supply system.
- Demand is Growing Rapidly: The population is projected to increase by over 35% by 2033, leading to an inevitable, consistent increase in electricity consumption across all feeders.
- Large Energy Deficit Exists: The projected energy per capita of approximately 100 KWh/year falls far short of the target of 350 KWh/year, underscoring the severity of the energy poverty in the area.
- Solar Energy is Critical: To meet the growing load and ensure energy access targets, Auchi requires approximately 98 MW of supplementary Photovoltaic (PV) energy capacity by 2033.

A. Recommendations

Based on the findings, the following actions are recommended for sustainable energy provision in Auchi:

- Develop a PV Master Plan: The government and private sector should immediately invest in a phased master plan for the deployment of the required 98 MW of PV capacity, focusing on both distributed generation and utility-scale solar farms.
- Promote Energy Equity: Policy should be directed to ensure that the new supplementary energy capacity is distributed equitably, addressing the long-term disparity observed in the supply to the Igbe Road feeder.
- Infrastructure Upgrade: Investment in modernizing the 11kV distribution network is necessary to integrate decentralized solar generation efficiently and reduce technical losses.
- Incorporate External Factors in Future Models: Future forecasting should integrate external factors such as economic growth and weather conditions to further enhance the accuracy of the regression models.

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